MALACOLOGIA, 2011, 53(2): 367–371

SURVIVAL OF THE INVASIVE CLAM *CORBICULA FLUMINEA* (MÜLLER) IN RESPONSE TO WINTER WATER TEMPERATURE

Oliver Müller & Bruno Baur*

Department of Environmental Sciences, Section of Conservation Biology, University of Basel, St. Johanns-Vorstadt 10, CH-4056 Basel, Switzerland

ABSTRACT

Water temperature plays a crucial role in determining the distribution of aquatic organisms because most are ectothermic. The further spread of the invasive Asian clam *Corbicula fluminea*, a species causing enormous damage to water intake pipes and electric power plant cooling systems, has been assumed to be limited due to intolerance of very cold water, with a lower lethal temperature of about 2°C. In recent years, however, *C. fluminea* invaded most of the major rivers in Europe, including sections where the water temperature falls below 2°C for short periods during winter. Here we quantify the cold tolerance of *C. fluminea* in a controlled laboratory experiment. We show that *C. fluminea* has a greater cold tolerance than previously assumed. In water of 0°C, clam survival decreased from 100% to 17.5% with increasing exposure from 4 to 9 weeks. Considering actual water temperatures of rivers during winter and ongoing stream warming, we conclude that this invasive clam will establish in a wider range of waterbodies in Europe than previously predicted.

Key words: Asian clam, biological invasion, cold tolerance, *Corbicula fluminea*, winter survival.

INTRODUCTION

Freshwaters are experiencing declines in biodiversity far greater than those in the most affected terrestrial ecosystems (Dudgeon et al., 2006). Besides water pollution, destruction or degradation of habitat and flow modification, the invasion of non-native species is a major threat to native freshwater biodiversity (Strayer, 1999). In the past decades, European inland waters have been increasingly affected by the colonisation of alien species, causing significant changes in aquatic communities (Baur & Ringeis, 2002; Baur & Schmidlin, 2007). Nowadays, more than 95% of the biomass of benthic macroinvertebrates in the river Rhine consists of non-native species (Bij de Vaate et al., 2002; Wirth et al., 2010).

Originating from Southeast Asia, the freshwater clam *Corbicula fluminea* (Müller, 1774) has been introduced in North and South America and in Europe (McMahon, 1983; Beasley et al., 2003; Morgan et al., 2003; Karatayev et al., 2005; Schmidlin & Baur, 2007). The rapid spread and persistence of *C. fluminea* throughout Europe, North and South America is related to its rapid growth rate, early onset of maturity, high fecundity, and its ability to tolerate a wide range of environmental conditions (Mattice & Dye, 1976; McMahon, 1983, 2002). In the river Rhine, *C. fluminea* was first recorded in The Netherlands in 1985 (Glöer & Meier-Brook, 1998). Since then, the invasive clam is spreading in rivers and standing waters, reaching densities of up to 10,000 individuals per m^2 (in the River Rhine near Basel; Mürle et al., 2008). *Corbicula fluminea* clogs water intake pipes, electric power plant cooling systems and sewage treatment plants, causing enormous damage (Pimentel et al., 2007). In the U.S.A., costs associated with this clam are estimated to be more than $1 billion per year (OTA, 1993). As a dominant species of the macrozoobenthos, *C. fluminea* is sequestering a large proportion of the carbon available for benthic production and altering the ecosystem functioning (Sousa et al., 2008). The invasive clam decreases the abundance of benthic flagellates, bacteria and diatoms and affects other organisms by bioturbating sediments (Hakenkamp et al., 2001). Valves of dead *C. fluminea*, however, can increase the surface area and substratum diversity of sandy bottoms,

---

*Corresponding author: bruno.baur@unibas.ch

resulting in an increase of benthic invertebrates (Werner & Rothhaupt, 2007).

The distribution of invasive freshwater species in novel areas is frequently determined by their tolerance to low and high water temperatures. The invasive *C. fluminea* has been widely perceived as limited in its range due to intolerance of cold water (McMahon, 1983). This reflects the relatively mild winter temperatures *C. fluminea* experiences in its native habitats in Southeast Asia. In a laboratory study of thermal tolerance, Mattice & Dye (1976) demonstrated that the incipient lower lethal temperature of *C. fluminea* was about 2°C. Since then, this lower lethal temperature has been cited repeatedly without further examination, even in the most recent *Handbook of Alien Species in Europe* (DAISIE, 2009). Using water temperature data of various rivers and considering 2°C as lower lethal temperature, Schöll (2000) predicted the spread of *C. fluminea* in Germany and concluded that without heat pollution, the species cannot establish in most rivers. In recent years, however, *C. fluminea* has spread in most of the major rivers in Europe, including sections where the water temperature falls below 2°C for short periods during winter (Schmidlin & Baur, 2007). Thus, the precise thermal tolerance of *C. fluminea* is not clear (Janech & Hunter, 1995), so it is impossible to predict its potential distribution range in Europe. Here, we present the results of a laboratory experiment designed to quantify the cold tolerance of *C. fluminea*.

MATERIALS AND METHODS

Corbicula fluminea is a simultaneously hermaphroditic filter- and pedal-feeding freshwater clam. It can reach sexual maturity at an age of 3–6 months (valve length of 6–10 mm) and reproduces by cross- and self-fertilization, releasing 300–400 pediveliger larvae of 200 μm length per day. In the River Rhine, *C. fluminea* is most abundant on fine-grained substrata (sand) with slowly flowing water (Schmidlin & Baur, 2007). Molecular analysis of a subunit of the mtCOI gene of *C. fluminea* revealed that all individuals collected in the rivers Rhine, Elbe and Upper Danube belong to the same haplotype (Stephanie Schmidlin, unpubl. data).

Specimens of *C. fluminea* were collected from the Altrhein, a remnant of the former river Rhine, 4 km downstream of Basel (47°37'29.7"N, 7°34'12.5"E) in March 2008. In the preceding three months these clams have been exposed to water temperatures ranging from 5.0 to 8.6°C. Prior to the experiment, the clams were acclimated to 8°C for seven days in containers filled with water from the River Rhine. We measured the size of each individual (maximum valve length) to the nearest 0.1 mm using a vernier calliper and assigned them to two groups: small clams (valve length 6.5–15.0 mm) and large clams (15.1–30.2 mm).

To examine the cold tolerance of *C. fluminea*, individuals were exposed to different water temperatures for periods of different lengths. The experimental design included the factors temperature (0°, 2° and 8°C), length of exposure (1, 2, 3, ..., 8, and 9 weeks) and size (small and large clams). Two replicates of 10 clams each were kept at each combination of factors (3 x 9 x 2) resulting in a total of 1,080 clams.

Following acclimation to 8°C for seven days, each ten small and ten large clams were placed in 10 x 11 x 9 cm compartments of plastic containers, whose bottoms were lined with 3 cm sand. Sand, sieved at a mesh size of 2 mm, was obtained from a site in the Rhine where *C. fluminea* occurred. Clams were submersed in water (6 cm) and the containers were kept in refrigerated incubators at constant temperatures of 0°, 2° and 8°C and darkness (clams are buried in sand during winter). To provide food (bacteria, phytoplankton) and oxygen, the water was exchanged every second day. Water from the River Rhine was cooled to the different experimental temperatures prior to exchange.

Every week we removed 20 clams (ten small and ten large individuals) per temperature treatment and replicate and tested their viability by forcing the tip of a dissection needle several millimeters between the posteriori valve margins in the region of the siphons (Matthews & McMahon, 1999). Living individuals strongly resist needle entry by tight clamping their valves. In contrast, dead clams offer little resistance and fail to close their valves after needle removal. The testing does not harm clams.

We used the R statistical computing software for data analysis (R Development Core Team, 2006). We applied a two-factorial ANOVA with repeated measurements to examine the effects of water temperature and duration of exposure on the survivorship of clams (Fig. 1). We used logistic regression to analyse any potential effect of individual clam size on survival. We built a generalised linear model (GLM) with a binomial error distribution and logit link (Fig. 2). The model consisted of the binary response variable (alive or dead) of each individual clam after a given exposure time and the independent categorical variable water temperature, and the two continuous variables length of exposure and individual clam size.

RESULTS

The water temperature significantly influenced the survival of overwintering *C. fluminea* ($F_{2.48}$ = 25.77, p < 0.0001; Fig. 1). Considering the entire experiment, 98.6% of the clams survived at 8°C, whereas 86.1% and 75.3% survived at 2° and 0°C, respectively. Furthermore, the length of exposure to cold water affected clam survival ($F_{1.48}$ = 99.86, p < 0.0001). Survival was constantly high at 8°C over the nine-week experiment. In water of 2° and 0°C, survival was high in the first four weeks, but decreased rapidly afterwards (interaction temperature x length of exposure: $F_{2.48}$ = 4.37, p = 0.0181; Fig. 1). Considering exclusively clams that were kept in cold water for 9 weeks, 47.5% survived at 2°C and 17.5% at 0°C.

Survival was also size-dependent ($F_{1.341}$ = 10.92, p = 0.0011; Fig. 2). In this analysis only clams that were exposed to different water temperatures for 7–9 weeks were considered. At 8°C, there was almost no mortality independent of valve size, whereas at 2°C and 0°C survival increased with valve size (Fig. 2). Larger clams had a higher probability to survive than smaller clams at water temperatures of 2° and 0°C (significant differences in the intercepts of the fitted lines, in each comparison p < 0.001). Survival was also size-dependent when all clams used in the experiment were considered ($F_{1.1025}$ = 9.73, p = 0.0019).

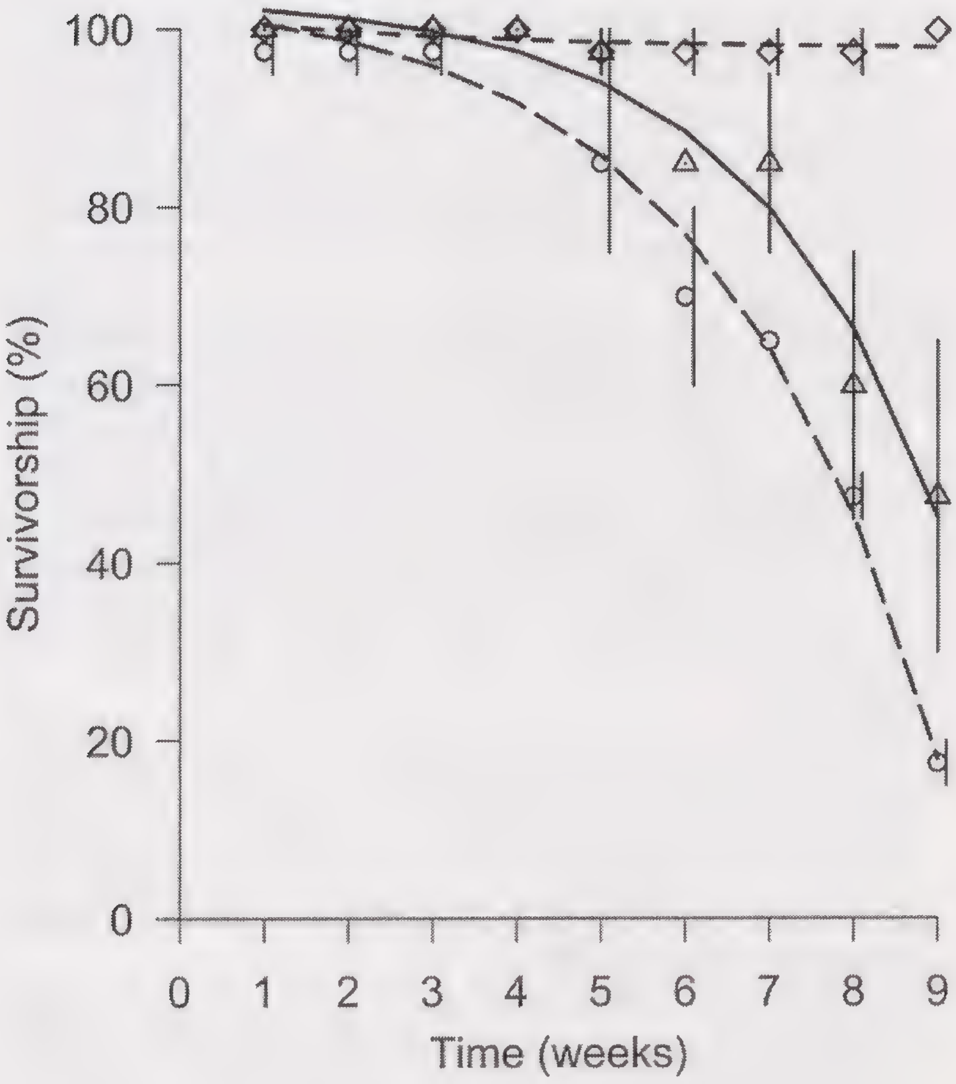

FIG. 1. Survival of *C. fluminea* exposed to water of different temperature (8°C, diamonds; 2°C, triangles; 0°C, open dots). Means (± 1 s.d.) of two replicates with 20 clams each are shown.

DISCUSSION

Our results show that *C. fluminea* has a much better cold tolerance than previously assumed. This could be explained by adaptation to cold water in temperate regions in the past decades, by phenotypic plasticity or by a non-optimal study of Mattice & Dye (1976) to determine the lower lethal temperature of this species. Janech & Hunter (1995) questioned the lower lethal temperature of 2°C because they recorded overwintering success of *C. fluminea* populations in North America despite water temperatures of 0–2°C for eight weeks. We also showed that clam survival in cold water decreased with exposure duration. In a ten-year field study in the Lower Connecticut river, New England, winter survival of *C. fluminea* was positively correlated with the average winter water temperature and negatively correlated with the frequency of daily mean water temperature ≤ 1°C (Morgan et al., 2003). In another study, condition indices decreased significantly in *C. fluminea* exposed to about 2°C for one month (French & Schloesser, 1996). Large individuals might have a better ability to store energy and therefore have a better resistance against different stressors than small clams. This could explain the size-dependent survivorship found in our study.

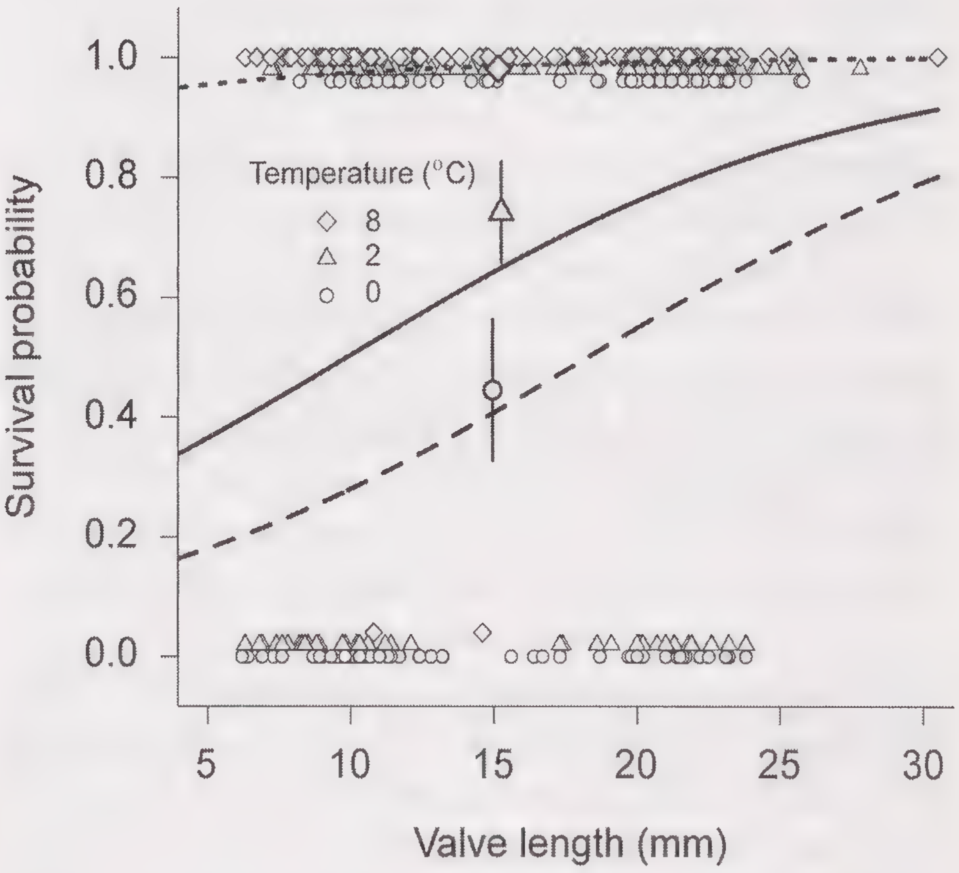

FIG. 2. Relationships between valve length of *C. fluminea* and the probability to survive in individuals exposed for 7–9 weeks to water of different temperature (lines show the model fit: 8°C, dotted line; 2°C, continuous line; 0°C, dashed line). Each symbol represents the status (alive or dead) of one individual. Mean survival probabilities and 95%-confidence intervals are also shown. At 8°C, there was almost no mortality independent of valve size, whereas at 2°C and 0°C survival increased with valve size.

The higher mortalities recorded at 2° and 0°C are most probably not a result of the abrupt temperature decrease at the beginning of the experiment following the pre-conditioning at 8°C, because clam survival was also high in the first four weeks at low water temperature. Our experiment simulated the conditions of an extended (and harsh) winter in a river fed with cold melt water. In most central European rivers, the water temperature falls below 2°C only for short periods of one to three weeks during winter. Our study shows that a significant portion of *C. fluminea* is able to survive short periods of cold water. However, when a period of extreme cold water exceeds two months, high mortality in *C. fluminea* may occur, as observed in Lake Constance in winter 2005/2006 (Werner & Rothhaupt, 2008).

The tolerance to low temperature may play a significant role in the future spread of *C. fluminea*. The length of cold water periods in rivers and lakes may limit the range expansion of this invasive clam. Eleven years (1997–2007) of daily water temperature data from 78 sites show that the minimum water temperature rarely falls below 2°C in most rivers in the Swiss lowlands (Müller, 2009). In a few rivers, the water temperature sank below 2°C for a period of 10–20 days in one to five years of the 11 years examined. During summer the water temperature of most rivers exceeds 16°C for at least one month which allows successful reproduction (Meister, 1997). In alpine rivers, however, the temperature requirements for clam survival and reproduction are not fulfilled. Niche modeling considering the temperature tolerance of the clam and extensive water temperature data revealed that almost all lowland rivers and lakes in Switzerland could be invaded by *C. fluminea* (Müller, 2009).

The spread of *C. fluminea* may be promoted by discharge of warmer industrial and residential water into natural waterways. In fact, downstream from cooling water outlets of power stations, populations of *C. fluminea* reach high densities (Morgan et al., 2003). Experimental warming in winter increased the clams' growth rate and enhanced the reproductive output (Weitere et al., 2009). From 1976 to 2000, mean air temperature at Basel and Zurich increased by 0.57°C per decade and stream temperature follows ambient air temperature closely (Hari et al., 2006). This means that global warming will facilitate the range expansion of invasive aquatic species (Heino et al., 2009). Our findings suggest that *C. fluminea* is able to establish in a much wider range of rivers and lakes than previously assumed.

ACKNOWLEDGEMENTS

We thank Peter Stoll for help with the data analysis and Anette Baur, Denes Schmera, Stephanie Schmidlin and two anonymous reviewers for comments on the manuscript.

LITERATURE CITED

BAUR, B. & B. RINGEIS, 2002, Changes in gastropod assemblages in freshwater habitats in the vicinity of Basel (Switzerland) over 87 years. *Hydrobiologia*, 479: 1–10.

BAUR, B. & S. SCHMIDLIN, 2007, Effects of invasive non-native species on the native biodiversity in the river Rhine. Pp. 257–273, in: W. NENTWIG, ed., *Biological invasions*. Springer, Berlin, xix + 441 pp.

BEASLEY, C. R., C. H. TAGLIARO & W. B. FIGUEIREDO, 2003, The occurrence of the Asian clam *Corbicula fluminea* in the Lower Amazon Basin. *Acta Amazonica*, 33: 317–324.

BIJ DE VAATE, A., K. JAZDZEWSKI, H. A. M. KETELAARS, S. GOLLASCH & G. VAN DER VELDE, 2002, Geographical patterns in range extension of Ponto-Caspian macroinvertebrate species in Europe. *Canadian Journal of Fisheries and Aquatic Sciences*, 59: 1159–1174.

DAISIE, 2009, *Handbook of alien species in Europe*. Springer, Berlin, 399 pp.

DUDGEON, D., A. H. ARTHINGTON, M. O. GESSNER, Z. I. KAWABATA, D. J. KNOWLER, C. LÉVÊQUE, R. J. NAIMAN, A. H. PRIEUR-RICHARD, D. SOTO, M. L. J. STIASSNY & C. A. SULLIVAN, 2006, Freshwater biodiversity: importance, threats, status and conservation challenges. *Biological Reviews*, 81: 163–182.

FRENCH, J. R. P. & D. W. SCHLOESSER, 1996, Distribution and winter survival health of Asian clams, *Corbicula fluminea*, in the St. Clair River, Michigan. *Journal of Freshwater Ecology*, 11: 183–192.

GLÖER, P. & C. MEIER-BROOK, 1998, *Süsswassermollusken*, 12th ed. Deutscher Jugendbund für Naturbeobachtungen DJN, Hamburg, 136 pp.

HAKENKAMP, C. C., S. G. RIBBLETT, M. A. PALMER, C. M. SWAN, J. W. REID & M. R. GOODISON, 2001, The impact of an introduced bivalve (*Corbicula fluminea*) on the benthos of a sand stream. *Freshwater Biology*, 46: 491–501.

HARI, R. E., D. M. LIVINGSTONE, R. SIBER, P. BURCKHARDT-HOLM & H. GÜTTINGER, 2006, Consequences of climate change for water temperature and brown trout populations in Alpine rivers and streams. *Global Change Biology*, 12: 10–26.

HEINO, J., R. VIRKKALA & H. TOIVONEN, 2009, Climate change and freshwater biodiversity: detected patterns, future trends and adaptations in northern regions. *Biological Reviews*, 84: 39–54.

JANECH, M. G. & R. D. HUNTER, 1995, *Corbicula fluminea* in a Michigan river: implications for low temperature tolerance. *Malacological Review*, 28: 119–124.

KARATAYEV, A. Y., R. G. HOWELLS, L. E. BURLAKOVA & B. D. SEWELL, 2005, History of spread and current distribution of *Corbicula fluminea* (Mueller) in Texas. *Journal of Shellfish Research*, 24: 553–559.

MATTHEWS, M. A. & R. F. MCMAHON, 1999, Effects of temperature and temperature acclimation on survival of zebra mussels (*Dreissena polymorpha*) and Asian clams (*Corbicula fluminea*) under extreme hypoxia. *Journal of Molluscan Studies*, 65: 317–325.

MATTICE, J. S. & L. L. DYE, 1976, Thermal tolerance of the adult Asiatic clam. Pp. 130–135, in: G. W. ESCH & R. W. MCFARLANE, eds., *Thermal ecology II*. National Technical Information Service, Springfield, Virginia, ix + 404 pp.

MCMAHON, R. F., 1983, Ecology of an invasive pest bivalve, *Corbicula*. Pp. 505–561, in: W. D. HUNTER, ed., *The Mollusca*, Vol. 6: *Ecology*. Academic Press, Orlando, 561 pp.

MCMAHON, R. F., 2002, Evolutionary and physiological adaptations of aquatic invasive animals: *r* selection versus resistance. *Canadian Journal of Fisheries and Aquatic Sciences*, 59: 1235–1244.

MEISTER, A., 1997, Lebenszyklus, Autökologie und Populationsökologie der Körbchenmuscheln *Corbicula fluminea* und *Corbicula fluminalis* (Bivalvia, Corbiculidae) im Inselrhein. Dissertation Technische Hochschule Darmstadt. *HLfU Umweltplanung, Arbeits- und Umweltschutz*, 238: 1–170.

MORGAN, D. E., M. KESER, J. T. SWENARTON & J. F. FOERTCH, 2003, Population dynamics of the Asiatic clam, *Corbicula fluminea* (Müller) in the Lower Connecticut River: establishing a foothold in New England. *Journal of Shellfish Research*, 22: 193–203.

MÜLLER, O., 2009, Temperaturtoleranz als limitierender Faktor für die weitere Ausbreitung der invasiven Körbchenmuschel *Corbicula fluminea* in der Schweiz? Masterthesis, University of Basel.

MÜRLE, U., J. ORTLEPP & P. REY, 2008, Koordinierte biologische Untersuchungen im Hochrhein 2006/2008. Makroinvertebraten. *Bundesamt für Umwelt, Bern, Umwelt-Wissen*, 822: 1–104.

OTA, 1993, *Harmful non-indigenous species in the United States*. Office of Technology Assessment, United States Congress, Washington, D.C., viii + 391 pp.

PIMENTEL, D., M. PIMENTEL & A. WILSON, 2007, Plant, animal, and microbe invasive species in the United States and world. Pp. 315–330, in: W. NENTWIG, ed., *Biological invasions*. Springer, Berlin, xix + 441 pp.

R DEVELOPMENT CORE TEAM, 2006, *R: a language and environment for statistical computing*. R Foundation for Statistical Computing, Vienna (http://www.R-project.org).

SCHMIDLIN, S. & B. BAUR, 2007, Distribution and substrate preference of the invasive clam *Corbicula fluminea* in the river Rhine in the region of Basel (Switzerland, Germany, France). *Aquatic Sciences*, 69: 153–161.

SCHÖLL, F., 2000, Die Wassertemperatur als verbreitungsregulierender Faktor von *Corbicula fluminea* (O. F. Müller 1774). *Hydrologie und Wasserwirtschaft*, 44: 318–321.

SOUSA, R., A. J. A. NOGUEIRA, M. B. GASPAR, C. ANTUNES & L. GUILHERMINO, 2008, Growth and extremely high production of the non-indigenous invasive species *Corbicula fluminea* (Müller, 1774): Possible implications for ecosystem functioning. *Estuarine, Coastal and Shelf Science*, 80: 289–295.

STRAYER, D. L., 1999, Effects of alien species on freshwater mollusks in North America. *Journal of the North American Benthological Society*, 18: 74–98.

WEITERE, M., A. VOHMANN, N. SCHLUTZ, C. LINN, D. DIETRICH & H. ARNDT, 2009, Linking environmental warming to the fitness of the invasive clam *Corbicula fluminea*. Global Change Biology, 15: 2838–2851.

WERNER, S. & K.-O. ROTHHAUPT, 2007, Effects of the invasive bivalve *Corbicula fluminea* on the settling juveniles and other benthic taxa. *Journal of the North American Benthological Society*, 26: 673–680.

WERNER, S. & K.-O. ROTHHAUPT, 2008, Mass mortality of the invasive bivalve *Corbicula fluminea* induced by a severe low-water event and associated low water temperatures. *Hydrobiologia*, 613: 143–150.

WIRTH, A., D. SCHMERA & B. BAUR, 2010, Native and alien macroinvertebrate richness in a remnant of the former river Rhine: a source for recolonisation of restored habitats? *Hydrobiologia*, 652: 89–100.

Revised ms. accepted 5 October 2010